

THE WORLD OF CHEMISTRY

Program #8

CHEMICAL BONDS

Producer John Ketcham

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Shots of the
natural world, explosion

NARRATOR (MUSIC and NAT
SOUND under):

Our world is filled with a vast variety of
different things: plants, animals, the sea
and air, rocks and minerals, yet
everything is made of atoms so small
they're invisible. Combinations of
atoms form these larger varied objects.
Energy is certainly involved in bonding
atoms, but how? If there is an
interatomic glue holding our world
together, what's the nature of that glue?
Intriguing and important questions,
because nearly all the substances around
us, and within us, are held together by
chemical bonds.

SUPER: CHEMICAL
BONDS

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in laboratory

ROALD HOFFMANN (SYNC):

Everything is made of atoms, but the building blocks of this world are groups of atoms, big or small in number, connected up to each other. So, in this flask of water there are 10^{24} or so water molecules, every one of them H_2O , in every one an oxygen connected up to two hydrogens. In this salt, there is a vast ordered array of sodium and chloride ions. We've got to figure out what it is that holds atoms together, in salt or in water. The key to chemical bonding is this marvelous periodic table of the elements, and a knowledge of the electron configurations of the atoms; in particular, those of the noble gases, like helium or neon. The noble gases are chemically inert. Why? Because they have a filled s and p electron cloud. Now, with very few exceptions, there are no compounds of the noble gases, but everything else in the periodic table, arsenic, copper, indium, nitrogen, sulfur, nickel, these do form compounds. They do so by trying to achieve the stable electron configuration of the noble gases. There are at least two ways to do that.

MONTAGE: Shots of
fluorescent lights using
different noble gases,
rain, lightning, algae

NARRATOR (MUSIC and NAT
SOUND under):

The elements in compounds are held together primarily by ionic or covalent bonds, and the basic rules governing how these bonds form are, first, atoms lose, gain, or share electrons to complete their valence shells; and second, electrons tend to exist in pairs. Only the six noble gases do not readily combine with other elements, because their valence shells are already full. Making and breaking these chemical bonds is chemical change, and when chemical change occurs, energy is involved. It might take a lightning bolt, or something as complicated as algae, to break a chemical bond.

Close up of chemical
reaction

NARRATOR (MUSIC and NAT
SOUND under):

What exactly are these bonds, and how do they form? Electrostatic attraction of oppositely charged particles, ions, forms one type of bond, called ionic bonding.

SUPER: IONIC
BONDING

How do ions form? Let's look at an alkali metal, sodium.

GRAPHIC: Valence
electrons and ionic
bonding

NARRATOR (MUSIC UNDER):

A sodium atom has one valence electron. Its energy level diagram looks like this. Very little energy is required to lose that electron. The outer shell is now full. A positive sodium ion has been formed, smaller than the atom. On the other side of the table, a chlorine atom has seven valence electrons. Energy is given off when it gains an electron, filling its valence shell, forming a negative chloride ion. When sodium and chlorine are brought together, one gives off an electron, the other accepts an electron. They react, producing an ionic crystalline solid, salt. Energy is involved, as demonstrator Don Showalter explains.

DS in lab

DON SHOWALTER (SYNC):

Now, what would happen if we would mix together sodium that wants to lose an electron, with chlorine that wants to acquire an electron. Let's see. In this beaker is chlorine gas. See the green color that's in there. That's quite a poisonous gas. What I want to do is to heat a piece of sodium metal. So I'm gonna put a piece into this glass spoon.
(cont.)

DON SHOWALTER cont:

I'm gonna melt it a little bit, get it in the bottom there, get it nice and molten, and put it inside here, and let's see what happens. That's quite a reaction, huh? A lot of light. It gets more and more intense. There's a white powder that's forming in there. And certainly the reaction is giving off a lot of energy. Now, once it calms down, let's see what it formed. There's a white crystalline material that has formed on the side of the beaker. That's sodium chloride, regular table salt. What we have done is to take two elements that are quite dangerous, and combined them into a substance that is essential for life.

GRAPHIC: Ionic structure
of sodium chloride crystal

NARRATOR (MUSIC under):

Sodium chloride, table salt, is a member of a huge family of salts, all crystalline solids. The electrostatic forces between the oppositely charged ions holds them together in the crystal. The electrical charge is evenly distributed over each ion. So ions of opposite charges are attracted from all directions. In sodium chloride, each chloride ion is surrounded by, and holds, six sodium ions. Each sodium ion is surrounded by, and holds, six chloride ions. This results in a rigid ordered pattern of alternating positive and negative ions. NaCl is the formula of sodium chloride. (cont.)

NARRATOR cont:

It implies there is one ion of sodium for each chloride ion. That one-to-one ratio of the ions exists throughout the cubic crystal. Dr. Jeffrey Post, a crystallographer for the Smithsonian Institution, studies mineral crystals, like salt.

INTERVIEW: Dr. Jeffrey Post, crystallographer, Smithsonian Institution

SUPER: Jeffrey Post

DR. JEFFREY POST (SYNC):

If you were to take a magnifying glass and look at these salt crystals from your salt shaker on your dinner table at home, you'd see that each of those little crystals looks exactly like this crystal, which is on a much smaller scale. And we've taken some crystals and looked at them on an electron microscope, and even at that scale, magnified hundreds of thousands of times, the crystal shapes are exactly the same, the same cubic shape. That's an inherent property of the structure.

GRAPHIC

NARRATOR (MUSIC under):

The lattice structure formed by the ions gives sodium chloride, and other salts, distinct properties unique to ionic compounds.

DS in lab

DON SHOWALTER (SYNC):

I have two crucibles. Both of them contain white crystalline solids. They look very much the same. However, one of them is ionically bonded. If the way substances are bonded together give them different properties, we ought to be able to test that. One way to do that is to see if they conduct electricity. We can do that by this sort of setup in here: light bulb, and electrode system. Let turn on the electricity -- and nothing happens. Well, sure, nothing's gonna happen, the circuit's open. Let me show you what happens if I close it with this screwdriver. The light comes on. How about this one? All right. Well, instead of using that screwdriver, what if we would lower the electrodes into the substances, test the conductivity that way? I'll lower them in there, and look what happens? Nothing. The light bulbs do not light up. Well, if one of them is ionically bonded, maybe because in the solid the ions aren't free to move around, what if we could help it by melting it? Oh, I hear something happening. Oh look. It's getting a little brown. I see some liquid coming around there. I've got all liquid, and this does not conduct electricity. So, in the molten form, this is a nonconductor, non-electrolyte. (cont.)

DON SHOWALTER cont:

Let's see what's happening over at the other crucible. I'm heating this one, and I have to heat it really hot, it looks like, in order for anything to happen. Oop! Here we go. Here we go! The light bulb is lighting. The bulb is lit. It must mean, now, that as we melt this substance it conducts electricity. So what we see is that this substance in this crucible is an electrolyte. The substance over here is a non-electrolyte, doesn't conduct electricity. Let's do one more test. I have two beakers here, each with a pair of electrodes in them. The electrodes are nice and clean. I'm gonna put in there some distilled water, pure water. Water into this one, and water into this one. Okay. Now, let me turn on the electricity with these switches, and let's see what happens. Nothing. Pure water does not conduct electricity. Now, into this beaker let's put some of this white solid, number one. Oh, and look what happened? The light comes on. When solid number one dissolves in water, it conducts electricity. It is an electrolyte. Let's try white solid number two. It looks pretty much the same. Put in there. Nothing happened. A little more. Nothing. Solid number two does not conduct electricity. It is a non-electrolyte. Now, what do you think these two solids are? (cont.)

DON SHOWALTER cont:

Well, solid number one was ordinary table salt, sodium chloride, and solid number two is ordinary sugar.

MONTAGE: Third
World scenes

NARRATOR (MUSIC and NAT
SOUND under):

Salt and human history are closely linked. Ancient people understood its value to life itself. Salt was once as valuable as gold. Good people are still the salt of the earth.

MONTAGE: Salt mine
equipment, salt ponds,
salt wells

NARRATOR (NAT SOUND under):

Today we produce nearly 40 million tons of sodium chloride a year, with half of it coming from caverns like this one, deep beneath the Louisiana Delta. The rest of our supply comes from huge evaporating ponds, or from salt wells. Very little of this salt actually reaches the table. Simple salt is needed by the chemical industry. Chlorine, sodium hydroxide, or lye, and sodium carbonate are all made from sodium chloride.

MONTAGE: Cows and
farm workers

NARRATOR (NAT SOUND under):
And salt is needed by most living things.
Cows seek salt instinctively. Whole
herds can be moved by simply moving
the salt lick. In mammals, salts are
practically all dissolved into solutions of
ions in bodily fluids. The concentration
of the proper ions must be maintained,
because that concentration actually
affects the cell membranes.

MONTAGE: Salt trucks,
archival footage of brushing
teeth, salt under microscope

EQUATION

NARRATOR (NAT SOUND under):
Other common salts are calcium
chloride, which is spread on streets to
melt ice. And stannous fluoride, the salt
of tin and fluorine, which is used in
toothpaste. These different salts might
have different crystalline structures.
The ion ratios and sizes may be
different.

INTERVIEW: Dr. Jeffrey
Post cont.

DR. JEFFREY POST (SYNC):
This is a calcite crystal, and the edges
come together at an angle, they're not
perfectly squared off like they were in
the salt or in the halite. And so this is a
property of the basic structure of
calcium carbonate. (cont.)

DR. JEFFREY POST cont:

The calcium ions and the carbonate ions stack together, and they repeat in three dimensions millions of times to build up a crystal, but, because of the different shape and the different charges of the carbonate molecules and the calcium ions, these stack together energetically in a different manner. And so the result is a crystal shape that looks quite different from that of the halite.

MONTAGE: Shots of
salt and salt containers

MUSIC

RH in restaurant

ROALD HOFFMANN (SYNC):

This table salt is our most commonly known ionic compound. But ionic bonding is not the only way that atoms can combine. Most substances around us are molecules held together in another way. Take this salad oil, or vinegar, or any molecule in my body, the atoms in these molecules are held together in a different way, by covalent bonding.

MONTAGE: Shots of
diamond, water, gases,
hot air balloon

NARRATOR (MUSIC and NAT
SOUND under):

Covalent bonding is the most common type of chemical bonding that holds atoms together in molecules. Molecules are electrically neutral combinations of different atoms. Unlike ionic substances, which are solids, molecular substances can be solids, liquids, or gases. To understand covalent bonding, let's begin with the simplest element, hydrogen.

SUPER: Covalent Bonding

GRAPHIC: Covalent
bonding

NARRATOR (MUSIC under):

Imagine two hydrogen atoms, each with one proton in the nucleus and one electron. Both atoms have the same energy and their valence shells are not complete. As they move towards one another, the electron clouds begin to overlap. They start sharing electrons. A molecule is forming. When the clouds overlap, the electrons are paired together, shared. The valence shells are complete and a covalent bond has been formed.

MONTAGE: Shots of
the sun

NARRATOR:

On the sun, at high temperatures,
hydrogen can exist as separate atoms.
But at far lower temperatures, here on
earth, hydrogen exists as molecules,
which have lower energy than the two
single atoms. Here that's the preferred
natural state.

GRAPHIC: Bonding and
energy

NARRATOR (MUSIC under):

So, as the two atoms move together and
the electron clouds begin to overlap,
forming the molecule H_2 , the energy
within this two-atom system decreases.
Whenever a covalent bond is formed,
energy is released. Where does the
energy go? It's released to the
surroundings.

MONTAGE: Blasting

NARRATOR (SFX: bomb blasts):

If controlled, that energy can move
mountains. In certain compounds,
chemical bonds are weak and can be
easily broken, freeing the atoms to
reform into molecules with stronger
bonds. When they do, an enormous
amount of energy is released. Most
conventional explosives contain nitrogen
atoms weakly bonded to other atoms.
Why nitrogen?

EQUATION

NARRATOR (NAT SOUND under):

Because, when nitrogen forms its molecule, N_2 , the atoms will share three pairs of electrons. The bond formed is one of the strongest known, and the energy released in the process makes nitrogen-based explosives unique, as Don Showalter will demonstrate.

DS in lab

DON SHOWALTER (SYNC):

Now, we've seen a little bit about nitrogen bonds, how two nitrogen atoms will combine to form a stable N_2 molecule. Now, iodine, a member of the halogen family, will also form a stable diatomic molecule. Now, you would think that the electrons in the nitrogen atom would be easily shared with 3 iodines, and you're right. Now, this small brownish pile that you see in front of you is nitrogen triiodide, nitrogen bonded to three iodine atoms. Nitrogen doesn't need much encouragement to go back to its elemental form, N_2 , and when it does that many times, the energy release is quite surprising. Let me show you. I'm gonna protect my ears by putting some cotton in them. And I'm gonna initiate this reaction by the touch of a feather. Let's watch. Wow! What a reaction. huh! (cont.)

EQUATION

DON SHOWALTER cont:

The nitrogen tri-iodide went to nitrogen, N₂, and iodine, I₂. You saw the purple iodine cloud that came out of there.

Now, this strong tendency of nitrogen to form that N₂ bond has many applications.

MONTAGE: Archival footage of blasting, tunnel building, modern blasting

NARRATOR (MUSIC and NAT SOUND under):

Explosives have impacted civilization in peace and in war. Tunnels, canals, excavations, and roadbeds were all made possible by these high-energy explosives. The trinitroglycerine of dynamite and TNT made mining more efficient, but the explosive of choice in today's blasting industry is a fertilizer.

Men preparing blasting holes

D. LINN COURSEN (VO):

The white stuff that's showing in there is a base load of ammonium nitrate and fuel oil.

NARRATOR (NAT SOUND under):

Ammonium nitrate, another nitrogen compound, is a fertilizer farmers use on their fields.

INTERVIEW: Linn
Coursen, research fellow,
ETI

D. LINN COURSEN (SYNC):
Now, these holes will go off in a time
sequence.

NARRATOR (NAT SOUND under):
Lynn Coursen is a research fellow at
ETI, the company supplying the
explosives for today's shoot.

INTERVIEW: Linn
Coursen cont.

SUPER: D. Linn Coursen

D. LINN COURSEN (SYNC):
What will happen is that the charges in
front will begin moving the rock out of
the way so that the charges in back will
not have as much rock to move out.

Workers preparing
blasting holes

NARRATOR (NAT SOUND under):
Each hole is filled with the ammonium
nitrate-fuel oil mixture and a primer of
TNT. In a fraction of a second, there
will be millions of chemical bonds
breaking and reforming to produce an
explosion.

Blasting of wall

NARRATOR (NAT SOUND under):
Four and a half tons of ammonium
nitrate were used in blasting away this
rock cliff.

GRAPHIC

MONTAGE: Shots of
clouds, water, birds,
lightning, farm fields,
farm machinery, roots
of soybeans, greenhouse

NARRATOR:

When any covalent bond forms, energy
is released. The same amount of energy
is needed in order to break that bond.

NARRATOR (MUSIC and NAT
SOUND under):

This is something nature does every day.
There is nitrogen in all living things.
Muscles, hair, and DNA all contain
nitrogen bonded to other elements. But
80 percent of the atmosphere is nitrogen
molecules held together by strong triple
bond. How do living things get the form
of nitrogen they need? Lightning helps.
The electrical flash in the sky has
enough energy to break apart nitrogen
molecules, which then react with oxygen
in the air, forming nitric acid. This
natural acid dissolves in rain and falls to
earth as a dilute solution. There it is
absorbed and metabolized by plants.
Some plants, though, convert molecular
nitrogen in a different way. Soybeans
and other legumes, like peas and
peanuts, host a unique bacterium in their
roots. It is this bacterium which
converts the nitrogen molecule into a
nitrogen compound, ammonia, which the
plant can then use to make amino acids.
(cont.)

NARRATOR cont:

Exactly how the bacterium works is the subject of vigorous research. From the U.S. Department of Agriculture, Don Keister.

INTERVIEW: Don Keister,
U.S. Department of
Agriculture

SUPER: Don Keister

DON KEISTER (SYNC):

This is one of the very unique enzymes in all of nature, because it is the only, it is the only solution that nature has come up with for biologically reducing nitrogen.

MONTAGE: Soybean,
bacterium under
microscope, farm
fields, farm
machinery

NARRATOR (NAT SOUND under):

The soybean and the bacterium have a symbiotic relationship. The plant houses and feeds the bacterium and, in turn, it receives the nitrogen it needs. But not all plants can host these nitrogen fixers. They have to rely on rain and manufactured fertilizers, like ammonium nitrate, and they're expensive. As the world's population grows, so does the demand for food, which depends on nitrogen fixation.

Shots of oil refineries

DON KEISTER (VO/SYNC):

We are currently using something like 300 million barrels of oil per year in this country alone to produce nitrogen fertilizers.

INTERVIEW: Don
Keister cont.

We, for instance, forget that we're going to need to double the food supply over the next 20 years. Where is that energy gonna come from? Where is the fertilizer gonna come from?

MONTAGE: Farm fields,
fertilizer, greenhouse

NARRATOR (NAT SOUND under):

For feeding the world, there are two basic options: We can either produce more fertilizer at greater cost and some risk to the environment, or we can create new varieties of nitrogen-fixing plants. Both options are being pursued worldwide.

MONTAGE: Ocean,
chemical reactions,
graphics, salt crystals,
lab demonstrations,
blasting, wheat

SUPER: CHEMICAL
BONDS

NARRATOR (MUSIC under)

To review, except for the noble gases like helium and neon, which have full valence shells, everything around us is chemically bonded. Ionic and covalent bonding are the two main ways which elements can bond. Ionic bonds form when atoms either give up or acquire electrons. In the process, they become positive or negative ions, which attract one another, producing salt crystals. Covalent bonds are formed when two or more atoms complete their valence shells by sharing electrons. As atoms form molecules, energy is released, so molecules have less energy than the initial atoms. To break molecules apart, back into their constituent atoms, energy must be put back into the system.

RH in office with models
of molecules

ROALD HOFFMANN (SYNC):

My own research actually has to do with bonding in molecules. What I want to know is why a molecule has the structure that it does. Let me tell you a story, something I did a few years ago.
(cont.)

ROALD HOFFMANN cont:

There is an important class of molecules called organometallics. They have an organic piece and a metal atom. One day a German group made a new one of these, tris(ethylene) nickel. It has in it ethylene and a nickel atom. Now, when they made it, they didn't know its shape, its structure, whether the ethylene was standing up, like soldiers, or if they should be lying down, the way they are in this model. Why does it matter?

Well, the shape of a molecule is important in defining its properties. Molecules close to this one were active as catalysts in making polyethylene. But that's not the reason why I was interested in them. I just wanted to know their geometry. Together with my co-workers, and looking at the way that the electrons move in this molecule, we were able to predict that the ethylenes should be lying down, the way they are now. Within a very short period of time, a group in England confirmed this prediction on a related platinum-containing molecule. You can see that this is a problem in molecular architecture. Chemical bonds are connections between atoms, of a definite strength, a definite length. They make molecules out of atoms. But knowing the bonding in a molecule is not sufficient. (cont.)

ROALD HOFFMANN cont:
Molecules also have a characteristic
shape, a structure, an architecture,
which we will see in the next program.

Credits, Closing Montage, Closing Music

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